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# Merger and Ring Galaxy Formation Rates at $z \leq 2$

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submitted to MNRAS

## ABSTRACT

We compare the observed merger rate of galaxies over cosmic time and the frequency of collisional ring galaxies (CRGs), with analytic models and halo merger and collision rates from a large cosmological simulation. In the Lambda cold dark matter model (LCDM) model we find that the cosmic *merger fraction* does not evolve strongly between  $0.2 \leq z \leq 2$ , implying that the observed decrease of the cosmic star formation rate since  $z \sim 1$  might not be tied to a disappearing population of major mergers. Halos hosting massive galaxies undergo on average  $\sim 2$  mergers from  $z \leq 2$  up to present day, reflecting the late assembly time for the massive systems and the related downsizing problem. The cosmic *merger rate* declines with redshift: at the present time it is a factor of 10 lower than at  $z \sim 2$ , in reasonable agreement with the current available data. The rate of CRG formation derived from the interactions between halo progenitors up to  $z = 2$  is found to be a good tracer of the cosmic merger rate. In the LCDM model the rate of CRGs as well as the merger rate do not scale as  $(1+z)^m$ , as suggested by previous models. Our predictions of cosmic merger and CRG rates may be applied to forthcoming surveys such as GOODS and zCOSMOS.

## Key words:

galaxies: interactions - galaxies: peculiar - methods:  $N$ -body simulations - cosmology: theory

## 1 INTRODUCTION

In a hierarchical Universe, galaxy mergers are thought to play an important role during structure formation, particularly at higher redshifts. Mergers may be also relevant to the growth of massive early-type galaxies (e.g. Toomre 1977; Barnes & Hernquist 1996; Naab et al. 2006; Cox et al. 2006). Simulations of mergers involving gas-rich discs suggest that major mergers can trigger violent starbursts and transform discs into spheroidals. However the role of mergers in the galaxy assembly and star formation processes is still unclear. The observed correlation between galaxy morphology and color indicates that the star formation history of a galaxy is closely tied to its morphology evolution. However, it has been recently recognized that there may be different timescales for the formation of stars in massive spheroidals. Thus, tracking the galaxy merger rate as a function of redshift can constrain the contribution of mergers to the formation of stars in spheroids.

Despite their importance, it has proved challenging to measure the rate of galaxy mergers and its evolution with cosmic time. Many theoretical and observational attempts have attempted to reconstruct the history of the galaxy in-

teraction rate (Toomre 1977; Zepf & Koo 1989; Carlberg 1990a, 1990b; Carlberg, Pritchet & Infante 1994; Burkey et al. 1994; Yee & Ellington 1995; Neuschaefer et al. 1995; Woods, Fahlman, & Richer 1995; Patton et al. 1997; Le Fèvre et al. 2000; Conselice, Bershadsky & Jangren 2000a; Conselice, Bershadsky & Gallagher 2000b; Bershadsky, Jangren & Conselice 2000; Conselice 2003; Conselice et al. 2003, 2004; Cassata et al. 2005; Conselice 2006; Bridge et al. 2007; Jogee et al. 2007; 2008; see Conselice 2007 for a short review).

Various models (Toomre 1977; Carlberg 1990a, 1990b) suggest that the galaxy merger rate per unit volume  $\dot{n}$  increases with the redshift  $z$  as:

$$\dot{n} \propto (1+z)^m, \quad (1)$$

The theoretical approach proposed by Carlberg (1990a, 1990b), based on the Press–Schechter formalism (Press & Schechter 1974), predicts that the value of the coefficient  $m$  depends on the present-day matter density parameter  $\Omega_M$ :

$$m \sim 4.51 \times \Omega_M^{0.42}. \quad (2)$$

More recently the Millennium simulation (Springel 2005) has been used to construct merger trees and to quantify the merger rates of halos, pointing out that the average merger rate per halo depends weakly on the halo mass and

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that the halo merger rate evolves with  $z$  as  $(1+z)^{2-2.3}$  (Fakhouri & Ma 2007). Due to the difficulty of directly observing the merger features, measurement of the redshift evolution of the fraction of galaxy pairs has traditionally been taken, which can be parametrized as  $\propto (1+z)^k$ . Most studies (Zepf & Koo 1989; Carlberg et al. 1994; Burkey et al. 1994; Yee & Ellington 1995; Woods et al. 1995; Patton et al. 1997; Kampczyk 2007) derive a value of  $k \sim 2-4$ , while Neuschaefer et al. (1995) find  $k \sim 0$ , due to a different estimate of the non-physical galaxy pairs. The main difficulty of this method is that the conversion from  $k$  to  $m$  is unclear. It is also difficult to disentangle projection pairs from true physical pairs when using photometric redshifts alone. Additionally, not all galaxies in a physical pair will merge, as the galaxies may be unbound.

From an observational point of view, it is difficult to estimate whether  $\dot{n}$  depends on the redshift and to determine the correct value of  $m$ . A direct measurement of merger features in distant galaxies is difficult, as tidal tails and distortions generally have low surface brightness (see Mihos 1995; Hibbard & Vacca 1997).

A powerful method for measuring the galaxy merger rate is to count the incidence of strongly disturbed galaxies (with strong asymmetries, double nuclei or prominent tidal tails), the so-called CAS method (Conselice 2003). There are several methods to quantify the frequency of strongly distorted galaxies: visual classification, quantitative measures of asymmetries such as the CAS system (Conselice 2003) and the Gini-M20 system (Lotz et al 2006).

All asymmetries suffer from surface brightness (SB) dimming, but the outer low SB features suffer more strongly from it. CAS misses the latter features, but visual classification captures many of these. Simulations (Conselice 2006) as well as empirical studies (Jogee et al. 2007, 2008) show that visual classifications capture a larger fraction of strongly distorted galaxies than the CAS merger criteria, as the eye is sensitive to asymmetries over a larger dynamic range.

The CAS method, applied to the *Hubble Deep Field* (HDF), provides an estimate of  $m$  ranging from 4 to 6 (Conselice et al. 2003; but  $m \sim 2-4$  in the re-analysis of these data by Conselice 2006). Based on the results of the CAS analysis, Conselice (2006) suggests that equation (1) is inaccurate for some galaxy types (especially for small galaxies) and for high redshifts ( $z \gtrsim 1-2$ ). The CAS method provides a more straight-forward estimate of merger rate than the incidence of close pairs of galaxies. However, positioning a galaxy in the CAS plane is sometimes problematic. Furthermore, the connection between high asymmetry/clumpiness and merger history implies a number of assumptions.

For these reasons, Lavery et al. (2004; hereafter L04) proposed to use ring galaxies as a more direct tracer of galaxy mergers. In fact, a high fraction of ring galaxies [ $\approx 60$  per cent, Few & Madore (1986)], called ‘P-type ring galaxies’, are thought to have collisional origin. Recent  $N$ -body simulations (Mapelli et al. 2008a, 2008b, and references therein) show that the ring phase is quite short-lived: it lasts only for  $\lesssim 500$  Myr after the galaxy collision. Moreover, ring galaxies are easier to identify than other interaction signatures (e.g. tidal tails; see Mihos 1995; Hibbard & Vacca 1997). Thus, the number of collisional ring galaxies (hereafter CRGs) may be a straight-forward tracer of the galaxy interaction rate.

Unfortunately, most ring galaxies with measured distances are relatively nearby [ $z \lesssim 0.1$ ; see e.g. the sample of 68 ring galaxies in Few & Madore (1986)].

L04 analyze 162 Wide Field Photo Camera 2 (WFPC2) fields, obtained from the *Hubble Space Telescope* (HST) Archives, in order to identify distant CRGs. They find 25 CRGs in their images. From this sample, L04 derive a value of the merger rate  $m \sim 5$ . However, their estimate is affected by large uncertainties, as they have redshift measurements only for 6 of their 25 CRGs. For the remaining 19 galaxies, they derive an ‘estimated redshift’, by assuming that CRGs have similar visual magnitude. Recently, Elmegreen & Elmegreen (2006, hereafter E06) analyzed other 24 CRGs in the GEMS and GOODS fields. For these galaxies redshift measurements are available.

In this paper we present an attempt to derive the merger and the CRG formation rate from cosmological simulations. The simulations can estimate the rate of minor and major mergers in progenitors of the present-day galaxy halos and establish whether the merger rates and CRG formation rates are related. We calculate the evolution of the merger and CRG formation rate up to redshift 2. Finally this study compares results from numerical simulations with the available data and gives predictions for future observations. In Section 2 we present details of the numerical simulation and analysis procedure. Section 3 discusses our main results, while Section 4 summarizes our conclusions and implications.

## 2 NUMERICAL METHODS

### 2.1 Simulations

We analyze a cosmological  $N$ -body simulation of the Lambda cold dark matter (LCDM) cosmogony, with cosmological parameters chosen to match the 3-yr Wilkinson Microwave Anisotropy Probe (WMAP3) constraints (Spergel et al. 2007). These are characterized by the present-day matter density parameter,  $\Omega_M = 0.238$ , a cosmological constant contribution,  $\Omega_\Lambda = 0.762$ , and a Hubble parameter  $h = 0.73$  ( $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). The mass perturbation spectrum has a spectral index of  $n = 0.951$ , and is normalized by the linear rms fluctuation on 8 Mpc/ $h$  radius spheres,  $\sigma_8 = 0.75$ .

We follow the evolution of  $600^3$  particles of mass  $m_{\text{dm}} = 8.67 \times 10^7 h^{-1} M_\odot$  in a box of 90 Mpc (or 65.7 Mpc/ $h$ ) (comoving) on a side, by using the  $N$ -body code PKDGRAV (Stadel 2001). Gravitational interactions between pairs of particles are softened with a fixed comoving softening length of 1.16 kpc.

### 2.2 Halo Identification and Merger Tree

Non-linear structures at  $z = 0$  are identified using the classic friends-of-friends (FOF) algorithm with a linking length equal to 0.2 times the mean comoving interparticle separation. For each FOF halo we identify the most bound particle and adopt its position as the halo centre. Using this centre, we compute the ‘virial radius’ of each halo,  $r_{\text{vir}}$ , defined as the radius of a sphere of overdensity  $\Delta(z = 0) = 94$  (rel-

ative to the critical density for closure)<sup>1</sup>. Quantities measured within  $r_{\text{vir}}$  will be referred to as ‘virial’, for short. We select for our analysis all halos with masses in the range  $M_{\text{vir}} = 5 \times 10^{12}$  to  $10^{14} h^{-1} M_{\odot}$ . The resulting halos have  $N_{\text{vir}}$  between 56,000 and 1,100,000 particles within the virial radius. The mass resolution and the number of particles in halos considered in the sample at present day guarantees that we do not miss any relevant major merger event and interaction of halos progenitors back in time.

The assembly history of each halo may be studied using halo catalogues analogous to the one just described, but constructed at various times during the evolution of the system. For the purposes of our analysis, we concentrate on the period  $0 < z < 2$ . Halos identified at  $z > 0$  are said to be ‘progenitors’ of a  $z = 0$  system if at least 50 per cent of its particles are found within the virial radius of the latter. Using this definition we can identify, at all times, the list of progenitors of a given  $z = 0$  halo and track their properties through time. Progenitors of interest contain at least 250 particles. To identify mergers, we denote a halo as a major merger remnant if at some time during  $0 < z < 2$  its major progenitor was classified as a single group in one output but two separate groups with a mass ratio  $\leq 4 : 1$  in the preceding output (see D’Onghia & Burkert 2004).

### 2.3 Ring Galaxy Formation Criteria

Since our simulations are based on dark matter only, we cannot directly trace the formation of CRGs. However, we can estimate the rate of CRG formation from our models adopting the following criteria. At each redshift we select a sample of progenitor halos in the range of mass of a few  $10^{11} M_{\odot}$  to  $5 \times 10^{12} M_{\odot}$  (corresponding to the typical masses of observed CRGs) and we consider the encounters between them. We consider a list of 8 progenitors ordered by decreasing mass and we examine the collisions between the most massive and the second most massive progenitor and all the possible combinations amongst progenitors along the list.

We assume that a CRG is formed whenever two halos undergo an encounter in which:

- i) the mass ratio between the bullet (hereafter ‘intruder’ halo) and the most massive progenitor (hereafter ‘target’ halo) is  $\geq 1 : 10$ ;
- ii) the pericentre distance  $p$  is less than  $\sim 15$  per cent of the expected disc radius of the target galaxy (i.e.  $p \leq 4$  kpc, Lynds & Toomre 1976).

The first constraint comes both from observations of nearby CRGs whose intruder is known, and from numerical simulations showing that the ring is hard to form when the mass ratio between the intruder and the target galaxy is  $\leq 1 : 10$  (Hernquist & Weil 1993; Mihos & Hernquist 1994; Horellou & Combes 2001; Mapelli et al. 2008a, 2008b).

The second condition assumes results from numerical simulations showing that circular rings form only when the impact parameter is small. The larger the impact parameters, the more asymmetric is the resulting ring (Hernquist

& Weil 1993; Mihos & Hernquist 1994; Horellou & Combes 2001; Mapelli et al. 2008a, 2008b).

Finally, we do not put any limitation on the inclination angle  $\theta$  (between the disc axis of the target and the velocity of the intruder). Lynds & Toomre (1976) indicated that relatively symmetric ring galaxies can form at least for  $\theta \leq 45^\circ$ . Recent simulations (Ghosh & Mapelli 2008) show that regular (although warped) rings form also for  $\theta > 60^\circ$ . So, we can reasonably assume that ring galaxies can form also for high values of  $\theta$ . Thus, our estimate of the CRG formation rate represents an upper limit and should be rescaled by an unknown factor  $1 - \cos(\theta) \geq 0.5$ .

## 3 RESULTS

### 3.1 Merger Fraction Evolution up to Redshift 2

To predict the merger fraction as a function of redshift using observations of galaxy pairs is a difficult task, due to the complexity of establishing the time over which the merger occurred. Estimates of merger fractions using galaxy pairs come from Patton et al. (2000, 2002), Le Fèvre et al. (2000) and Lin et al. (2004) for  $z < 1$ . However, owing to projection effects, some pairs might not be a physically bound system and merging may last for a long time or may never occur.

On the other hand, in simulations we assume that a merger occurs when the smaller halo enters into the virial radius of the host halo, whereas the distance between the observed pairs is generally smaller than the virial radius of the progenitor. In fact, the baryonic component of the two galaxies is within  $\approx 20$  per cent of the virial radius.

A comparison of the merger rates extracted from the simulations for dark halos to galaxy merger rates has some limitations. A direct comparison implies a conversion between halo mass and galaxy mass/light. Many models usually adopted to this conversion, e.g., see van den Bosch et al. (2007) and reference therein, have a strong dependence upon halo (or galaxy) mass. These models point out that a merger between a dark matter halo and another halo of one-tenth its mass may not be equivalent to a merger between a galaxy and another one of one-tenth its mass.

The timescale over which the merger between a pair of galaxies is deemed visible is estimated as a fraction of the crossing time  $t_{\text{cr}}$  of the infalling halo into the host halo. The crossing time for realization of 1:1 merger simulations is  $\approx 1$  Gyr. Simulations of 1:1-1:2-1:3 mergers show that the timescale over which merger features are visible is  $\approx 0.5$  Gyr for systems with different orbital inclinations (Conselice 2006).

We therefore define the halo merger fraction  $f_{\text{merg}}$  as

$$f_{\text{merg}}(t, M) = \frac{N_{\text{merg}} t_{\text{cr}}}{N_{\text{tot}} \Delta t}, \quad (3)$$

where  $N_{\text{tot}}$  and  $N_{\text{merg}}$  are the total number of halos and the number of halos undergoing a (minor or major) merger at a given time interval  $\Delta t$  and for a given mass  $M$ , respectively.  $t_{\text{cr}}/\Delta t$  is the fraction of the time interval over which the merger signature is visible. In the time interval between  $z=0$  and  $z=0.3$  the time is longer than the merger time so we did not account for the time delay  $t_{\text{cr}}/\Delta t$ .

Table 1 lists the number of major and minor mergers and the total number of halos derived in simulations. In

<sup>1</sup> The virial overdensity in a flat universe may be computed using the fitting formula proposed by Bryan & Norman (1998):  $\Delta(z) = 18\pi^2 + 82 f(z) - 39 f(z)^2$ ; with  $f(z) = \frac{\Omega_0(1+z)^3}{\Omega_0(1+z)^3 + \Omega_\Lambda} - 1$

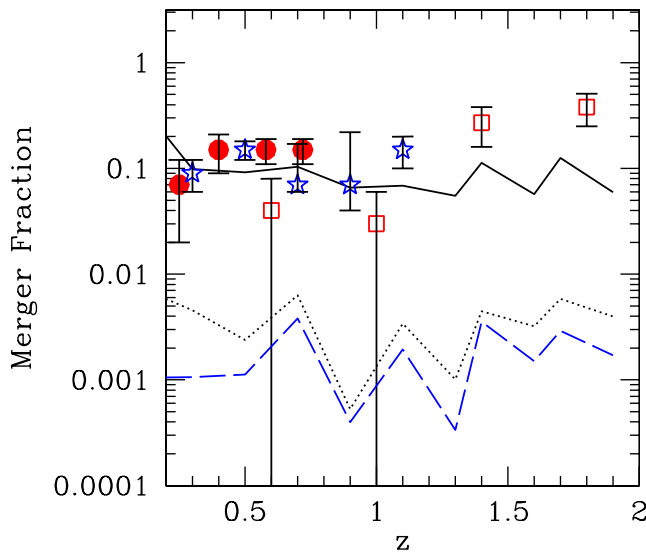
**Table 1.**

Minor and Major Mergers.

$z$	Mergers <sup>a</sup>	Major Mergers <sup>a</sup>	Mergers <sup>b</sup> [ $M \sim 10^{12} M_{\odot}$ ]	Major Mergers <sup>b</sup> [ $M \sim 10^{12} M_{\odot}$ ]
0.0	571	11	—	—
0.1	837	19	3	3
0.3	649	30	11	7
0.5	655	17	30	8
0.7	706	43	65	26
0.9	496	4	74	3
1.1	424	21	91	12
1.3	326	6	87	2
1.4	254	10	91	8
1.6	267	15	88	7
1.7	302	14	82	7
1.9	210	14	69	6

<sup>a</sup> Total Mergers(minor+major) and major mergers from simulations for halos at present day in the range of mass between  $5 \times 10^{12}$  and  $10^{14} M_{\odot}$ .

<sup>b</sup> Total Mergers(minor+major) and major mergers from simulations for progenitors with fixed mass between  $9 \times 10^{11}$  and  $3 \times 10^{12} M_{\odot}$  at any redshift.



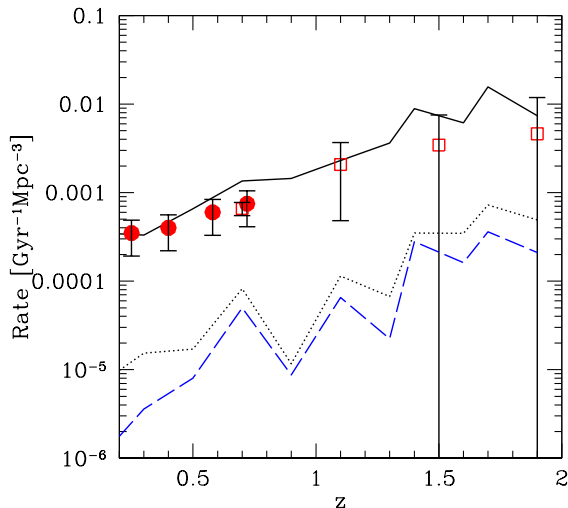
**Figure 1.** Total merger fraction (solid line) and major merger fraction (dotted line) of dark halos with mass between  $5 \times 10^{12}$  and  $10^{14} M_{\odot}$  at present day, as a function of redshift, derived from cosmological simulations. The long-dashed line shows the major merger fraction of Milky-Way sized halos at any time. Symbols represent empirical results on the merger fraction or fraction of strongly distorted galaxies identified via different methods, ranging from visual classification to automated methods: Jogee et al. (2007, 2008, filled circles), Le Fèvre (2000, filled squares), Conselice (2003, open squares) and Lotz et al. (2006, stars). Note that a stellar mass cut off was applied in Jogee data points ( $M_* > 2.5 \times 10^{10} M_{\odot}$ ) and in Conselice 2007 ( $M_* > 1 \times 10^{10} M_{\odot}$ ).

Figure 1 major merger fractions (the dotted line) and total (i.e. minor+major) merger fractions (solid line) derived from simulations are plotted as a function of redshift when assuming  $t_{\text{cr}} = 1$  Gyr. Our models predict a merger fraction that does not evolve significantly with redshift between  $0.2 \leq z \leq 2$ .

This implies that the observed decrease of the cosmic star formation rate since  $z \sim 1$  (e.g. Lilly et al. 1996; Madau et al. 1996) is not tied to a disappearing population of major mergers, and seems to be in agreement with recent new results by Jogee et al. (2007; 2008) for  $z \sim 0.2 - 0.8$ , and by Wolf et al. (2005) and Bell et al. (2005) at  $z \sim 0.7$ . Table 1 also lists the number of total mergers (minor+major) and major mergers for Milky Way sized progenitors identified at any time, with typical mass of  $\sim 10^{12} M_{\odot}$ .

In Figure 1 we compare the predictions of our models with data of the merger fraction, or fraction of strongly distorted galaxies, identified via different methods and based on different surveys : Jogee et al. (2007, 2008, filled circles), Le Fèvre (2000, filled squares), Conselice (2003, open squares) and Lotz et al (2006, stars). The results of Jogee et al. (2007, 2008) refer to the the fraction of strongly distorted interacting/merging massive (with stellar mass  $M_* > 2.5 \times 10^{10} M_{\odot}$ ) galaxies over  $z \sim 0.24$  to 0.80, identified from the GEMS survey (Rix et al. 2004) using both the CAS system and an independent visual classification system, specifically designed to separate interacting galaxies with externally-triggered asymmetries from non-interacting galaxies with small-scale internally-triggered asymmetries.

The presence of wiggles in the theoretical estimates is due to the uncertainty of using the merger tree to identifying mergers between progenitors at each time. The major merger fraction of Milky-Way sized halos identified at any time is displayed with the long dashed line. We note that the predicted fraction of major mergers and minor mergers is almost constant from  $z=2$  up to present day for Milky-Way sized halos identified at any redshift and for all the halos of our sample, regardless the mass. Furthermore, the agreement between merger fractions predicted from cosmological simulations (based on the halo merger history) and the observed merger fractions based on galaxy CAS morphologies is encouraging for the LCDM model.



**Figure 2.** Total merger rate (major+minor) (solid line) and major merger rate only (dotted line) of dark matter halos, per unit volume (comoving), as a function of redshift, derived from cosmological simulations. The rate per unit volume of Milky Way sized halos identified at any time is plotted for comparison (long-dashed line, blue on the web). Filled circles: rate of mergers and interactions, with mass ratios in the range 1:1 to 1:10, derived by Jogee et al. (2007, 2008) from the GEMS data. Open squares: merger rate from the HDF from Conselice (2003).

### 3.2 Merger Rates

The merger fraction is related to the merger rate per unit volume  $R$ , defined within a time interval and mass range, by the following expression.

$$R(t, M) = f_{\text{merg}} \tau_m^{-1} n_m, \quad (4)$$

where  $\tau_m$  is the timescale for a merger to occur and is defined as  $\approx t_{\text{cr}}$  and  $n_m$  is the physical density of the halos undergoing a merger (minor or major) within a given mass range and at a given time. The physical density of merging halos is derived by dividing the total number of halos which are merging  $N_{\text{merg}}$ , listed in Table 1, by the physical volume occupied by all the considered halos.

Figure 2 plots the major merger rate (dotted line) and the total merger rate (minor+major) (solid line) per unit volume, as a function of redshift, as derived from cosmological simulations. For comparison, Figure 2 also shows the merger rate inferred from the GEMS sample (Jogee, private communication; marked with filled circles) and the analysis of Conselice et al. (2007) based on the *Hubble Ultra Deep Field* (HUDF, open squares). For completeness, the plot displays the major merger rate per unit volume inferred in cosmological models for progenitors in the range of mass of the Milky way ( $\sim 10^{12} M_{\odot}$ ), identified at any redshift (long-dashed line). A large fraction of the progenitors are in this range of mass at higher redshift, explaining why these systems show a similar trend in the merger rate as the major mergers of all the halos. The merger rate of Milky Way sized halos (long-dashed line) decouples from the total major merger rate (dotted line) only at  $z \lesssim 0.5$ , where the former drops, while the latter decreases more gently. This is due to

the fact that mergers occurring at late time mainly involve the assembly of larger mass systems.

Note that the decrease of the volume-averaged merger rate at late times is a result of the decrease of the progenitor number density at lower redshift. Our predictions are in good agreement with the observations, despite the large uncertainties in the available data.

Summing over all mergers for massive halos ( $> 5 \times 10^{12} M_{\odot}$ ), we find that the average number of mergers a halo experienced since  $z \sim 2$  is  $N_m \sim 2$  in agreement with estimates of Conselice et al. (2007).

### 3.3 Ring Galaxy Formation Rate

First we check the correspondence between the CRG formation rate and the halo merger rate within our cosmological simulation. For CRGs we consider only halo progenitors with mass between a few  $10^{11}$  and  $5 \times 10^{12} M_{\odot}$  at any time, which correspond to the observed masses of ring galaxies. Figure 3 shows the CRG formation rate (lightly hatched histogram, red on the web), compared with the total (minor+major) merger rate of all the halos with present day masses between  $5 \times 10^{12} M_{\odot}$  and  $10^{14} M_{\odot}$  (open histogram, blue on the web). Both the CRG formation rate and the merger rate increase at lower redshifts. The null hypothesis probability that ring galaxies and mergers are drawn from the same distribution from redshift 0.2 up to  $z=2$  is  $\sim 0.11$ , corresponding to a non-reduced  $\chi^2 = 17.1$  (for 11 data points, 0 parameters, and assuming Poissonian errors). Thus, we conclude that the CRG formation rate can be considered a tracer of the merger rate.

Finally, we remark that our simulations follow the merger history and dynamics of dark halos and neglect processes involving the baryonic physics. In particular, the formation of galaxy discs, which is crucial for the formation of CRGs, cannot be modeled here. Also the time evolution for the late and early type number fraction is not accounted.

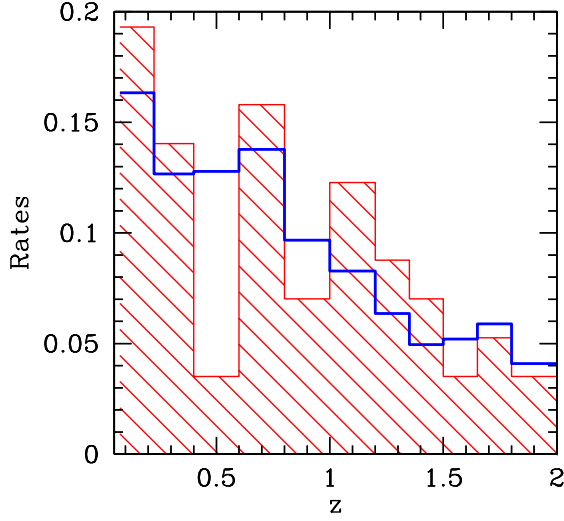
### 3.4 Comparison with Observations

The available data of moderately high redshift CRGs consist of a sample of 25 ring galaxies ( $0.2 \leq z \leq 1$ ), observed with *HST* (LO4), and a more recent sample of 24 ring galaxies ( $0.07 \leq z \leq 1.5$ ) found in the GEMS and GOODS fields (E06). Table 2 reports the number of CRGs observed in these two samples, as well as the number derived from our simulations.

Unfortunately, a direct redshift estimate has been provided only for 8 of the CRGs of the LO4 sample<sup>2</sup>. LO4 proposed to estimate the redshift of CRGs by adopting a ‘standard’ absolute  $V$  magnitude for CRGs (Appleton & Marston 1997).

Note that only the estimated redshifts ( $z_{\text{est}}$ ) are shown

<sup>2</sup> Redshift estimates are provided for 6 of the 25 galaxies of the LO4 sample, in particular the estimates reported in Table 1 of LO4 refer to CRGs identified with number 2; 3; 5; 7; 10; 20. Two more galaxies of that sample (CRGs labeled as 9 and 12) are members of galaxy clusters CL 0303+1706 ( $z = 0.6564$ ) and CL 1601+4253 ( $z = 0.5382$ ), respectively (see e.g. Dressler & Gunn (1992) for the redshift determination).



**Figure 3.** CRG formation rate (i.e. the number of newly formed CRGs in the entire simulation per redshift interval, lightly hatched histogram, red on the web) as a function of redshift, compared with the merger rate obtained considering all the halos in the range of mass between  $5 \times 10^{12} M_{\odot}$  and  $10^{14} M_{\odot}$  at  $z = 0$  (open histogram, blue on the web; see Table 1 and Fig. 2). The histograms are normalized so that their total area is 1.

**Table 2.** Number of simulated and observed CRGs.

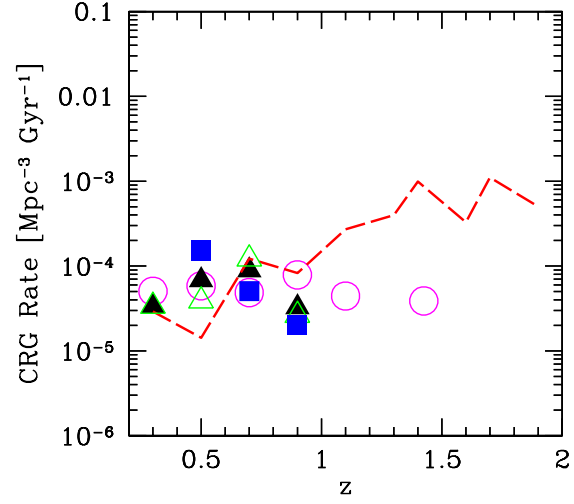
$z$	simulated CRGs <sup>a</sup>	L04 <sup>b</sup>	E06
0.1	11	—	1
0.3	8	2	2
0.5	2	7	4
0.7	9	11	4
0.9	4	5	8
1.1	7	—	4
1.3	5	—	—
1.4	4	—	1
1.6	2	—	—
1.7	3	—	—
1.9	2	—	—

<sup>a</sup> CRGs from our simulation (considering halos with mass between  $\sim 10^{11}$  and  $5 \times 10^{12} M_{\odot}$ ). The total number of CRGs in the simulation, from  $z = 0.1$  to  $z = 2$  (from  $z = 0.2$  to  $z = 1$ ) is 57 (23).

<sup>b</sup> The redshift is observed for 8 galaxies in the L04 sample (see the Text for details). An estimated redshift (L04) has been used for the 17 CRGs without redshift measurement. Note that the area of the survey is different from the one of our simulation (see text for details).

in figure 4 of L04, even for those CRGs that have an observed redshift ( $z_{obs}$ ). Also, the difference between  $z_{est}$  and  $z_{obs}$  is  $\gtrsim 10$  per cent, i.e. half of the bin width, for 4 of the 8 CRGs with known redshift. Yet, for 3 of these 4 galaxies the observed redshift  $z_{obs}$  is significantly smaller than the estimated value  $z_{est}$ .

This discrepancy has important consequences in the es-



**Figure 4.** CRG formation rate per unit volume (comoving). Open triangles (case L04old, green in the online version): the sample of 25 observed CRGs in L04 with  $z_{est}$  (the same as in figure 4 of L04). Filled squares (case L04 $z_{obs}$ , blue in the online version): the 8 observed CRGs with  $z_{obs}$  (CRG number 2, 3, 5, 7, 9, 10, 12 and 20 of L04). Filled triangles (case L04new, black in the online version): the 8 observed CRGs with  $z_{obs}$  and the remaining 17 observed CRGs with  $z_{est}$ . Open circles (magenta in the online version): CRG rate per unit volume derived from the E06 data. Long dashed line (red in the online version): simulated CRGs.

timate of the CRG formation rate. In Figure 4 the CRG formation rate per unit volume<sup>3</sup> of the CRG sample observed by LO4 is shown as a function of redshift. For the open triangles (hereafter case ‘L04old’) of Figure 4, we assumed the estimated redshift  $z_{est}$  reported in LO4 for all the 25 CRGs (including the 8 CRGs with measured redshift  $z_{obs}$ ). Note that the case L04old is the same as figure 4 of L04. The formation rate of the 8 CRGs with observed redshift  $z_{obs}$  is represented by the filled squares of Figure 4 (hereafter ‘L04 $z_{obs}$ ’). Note that the ring galaxy formation rate of the sample of LO4 peaks at  $z = 0.7$  when  $z_{est}$  is assumed (L04old), whereas the peak shifts to  $z = 0.5$  when  $z_{obs}$  is assumed instead (L04 $z_{obs}$ ).

For completeness, we plot the rate of formation of 25 CRGs of LO4 when  $z_{obs}$  is assumed for 8 galaxies which have an observed redshift and  $z_{est}$  assumed for the remaining 17 CRGs (filled triangles, hereafter ‘L04new’). The distribution peaks at  $z \sim 0.7$ . The open circles in Figure (4) represent the CRG formation rate derived using the data reported by E06. In this case all the redshifts are measured (either with spectroscopy or photometry).

We additionally plot in Figure 4 the CRG formation rate per unit volume derived from cosmological simulations, as a function of redshift (dashed line). Note that the CRG formation rate is derived from Table 2 and is the same

<sup>3</sup> The total solid angle of the observations in L04 and in E06 was  $\sim 7.31 \times 10^{-5}$  sr and  $\sim 4.87 \times 10^{-5}$  sr, respectively, independent of redshift.



as shown in Figure 3, but with a different normalization. The simulated CRG formation rate per unit volume approximately matches the data points in the redshift range  $0.2 \leq z \leq 0.8$ .

We also note that in our simulations the CRG formation rate per unit volume substantially increases with redshift. As already noted for the merger rate, this is mainly due to a substantial increase of the number density of progenitors present in merger tree at higher redshift.

At  $z \sim 1.1 - 1.5$  our simulated CRG formation rate is a factor of  $\sim 6 - 22$  higher than the one derived from E06 data. This might be due to several factors. First, we assume that all progenitors with mass  $10^{11} - 5 \times 10^{12} M_\odot$  and experiencing interactions with small impact parameter are disc galaxies, but the morphology of the progenitor cannot be inferred from our dark matter only simulations. Second, the E06 sample might be considered incomplete at  $z > 1.1$ .

Thus, new redshift measurements of moderately high-redshift CRGs will be extremely useful. The future survey zCOSMOS (Lilly et al. 2007) will acquire spectra and redshifts of approximately 10,000 galaxies ( $0 < z < 3$ ) in the COSMOS survey field and will derive for 10,000 galaxies between  $0 < z < 1$  the mass, the morphology and the size. This will provide an excellent sample to compare with the rate of CRGs predicted from our models.

### 3.5 Evolution of the Number of CRGs with Redshift

Various theoretical models suggest that the galaxy merger rate per unit volume scales with the redshift as  $\dot{n} \propto (1+z)^m$ . The exact value of  $m$  depends on the details of the adopted formalism, as well as on the cosmological parameters. Approaches based on the Press-Schechter formalism (Carlberg 1990a, 1990b) predict  $m \sim 2.5$ , assuming  $\Omega_M = 0.238$  from the WMAP3 constraints.

We showed in Figure 3 that the CRG formation rate is a good tracer of the merger rate. Hence, one might assume that also the CRG rate scales with  $(1+z)^m$  (L04). Thus, we derive the value of  $m$  from the simulated CRGs. In particular, the expected number of CRGs ( $N_{\text{CRG}}(z_1, z_2)$ ), which form between  $z_1$  and  $z_2$ , in a given volume, under the assumption that the density of CRGs scales as in equation 1, may be expressed by the following formula (see section 3.2 of L04).

$$N_{\text{CRG}}(z_1, z_2) = n_{\text{CRG},0} \left( \frac{c}{H_0} \right)^3 \times \int_{z_1}^{z_2} (1+z)^m \left[ \int_0^z \frac{dz}{\mathcal{E}(z)} \right]^2 \frac{dz}{\mathcal{E}(z)} \Delta\Omega(z), \quad (5)$$

where  $c$  is the light speed,  $n_{\text{CRG},0} \sim 5.4 \times 10^{-6} h^3 \text{ Mpc}^{-3}$  is the current density of CRGs (Few & Madore 1986),  $\mathcal{E}(z) = [(1+z)^3 \Omega_M + \Omega_\Lambda]^{1/2}$  and  $\Delta\Omega(z)$  is the considered solid angle at a given redshift  $z$ .

In the simulations  $\Delta\Omega(z)$  is the total solid angle, at a given  $z$ , occupied by our halo sample.  $\Delta\Omega(z)$  has been calculated as the sum of the physical sizes of each halo in the simulation divided by the comoving distance at a given  $z$ , i.e.

$$\Delta\Omega(z) \simeq 8.6 \times 10^{-4} \text{ sr} \left( \frac{a}{0.769} \right)^2 \left( \frac{\int_0^z \frac{dz}{\mathcal{E}(z)}}{0.283} \right)^{-2}, \quad (6)$$

**Table 3.** Number of expected CRGs in our simulation, as a function of  $m$ , in the redshift range  $z_1, z_2 = (0.2, 1.0)$  (central column) and  $z_1, z_2 = (0.2, 2.0)$  (right column).

$m$	$N_{\text{CRG}}$ ( $z_1 = 0.2, z_2 = 1.0$ )	$N_{\text{CRG}}$ ( $z_1 = 0.2, z_2 = 2.0$ )
1	6.7	10.0
2	10.4	18.5
3	16.5	36.4
4	26.7	76.5
5	44.0	170.1
6	73.8	397.1

where  $a$  is the cosmological factor of expansion. The equation (6) is normalized to  $z = 0.3$ .

Solving equation (5) for the values of  $\Delta\Omega(z)$  derived in equation (6) gives the expected number of CRGs which form in our simulations between  $z_1$  and  $z_2$ , provided that the CRG density scales with  $(1+z)^m$ .

We calculated equation (5) for different values of  $m$  and for  $(z_1, z_2) = 0.2, 1.0$  and  $(z_1, z_2) = 0.2, 2.0$ . Results are reported in Table 3. Our cosmological simulations show that 23 CRG form between  $z_1 = 0.2$  and  $z_2 = 1.0$ , leading to the value of  $m \sim 3.7$ , which is lower than the one obtained by L04 ( $m \sim 5$ ). However, if we consider the simulated CRGs forming up to  $z_2 = 2$ ,  $m$  is slightly lower: 46 CRGs are expected to form if  $m \sim 3.3$ .

If we adopt the model by Carlberg (1990a, 1990b), a value of  $m = 3 - 4$  is in disagreement with the cosmological parameters measured by WMAP3. In fact, equation (2) implies  $\Omega_M \sim 0.38 - 0.76$  for  $m = 3 - 4$ , at odds with the estimate of WMAP3.

*Viceversa* if  $\Omega_M = 0.238$  is assumed, in agreement with WMAP3 data, a value of  $m \sim 2.5$  is derived from equation (2). For  $m \sim 2.5$  the predicted number of newly formed CRGs in simulations up to  $z \sim 1$  is  $\approx 13$  (see Table 3), too low with respect to the observations of L04.

Furthermore, in the bottom panel of Figure 5 we plot the evolution in redshift of the number of CRGs obtained in cosmological simulations (hatched histogram) compared with the number of CRGs predicted from equation (5) (open histogram with dashed line). We note the different evolution of the two distributions with redshift: the former decreases, the latter increases with redshift. The null hypothesis probability that the two histograms are drawn from the same distribution is 0.19, corresponding to a non-reduced  $\chi^2 = 12.4$ . (with 10 data points, 1 parameter, and assuming Poissonian errors).

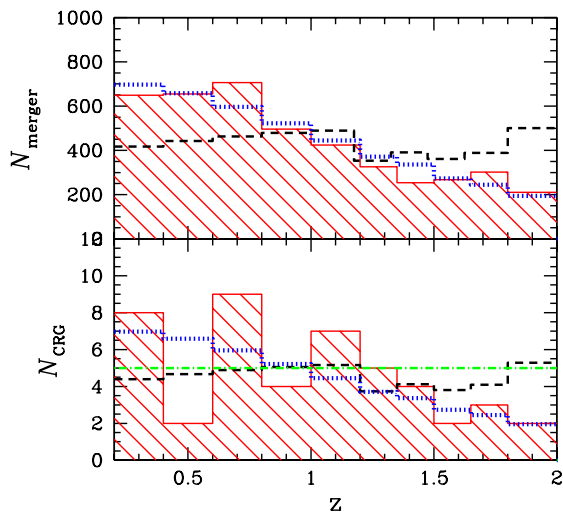
We also compare the number of CRGs obtained in our cosmological simulations with the fitting function proposed by Conselice (2006) [see equation (5) of Conselice (2006)]. The fitting formula by Conselice (2006), adapted for our simulated CRGs, can be written as

$$N_{\text{CRG}}(z) = \gamma (1+z)^m \exp[\beta(1+z)], \quad (7)$$

where  $\gamma=50$ ,  $m=2.4$  and  $\beta=-2.0$  best fit the simulated CRG distribution (between  $z = 0.2$  and  $z = 2.0$ ), reported in Figure 5.

In this case, the non-reduced  $\chi^2$  is 7.5, leading to a null hypothesis probability equal to 0.38 (considering 10 data points, 3 parameters, and assuming Poissonian errors).





**Figure 5.** *Bottom panel:* number of newly formed CRGs as a function of redshift. Hatched histogram (red in the online version): simulated CRGs. Open histogram with dashed line: model expressed by equation (5) for  $m = 3.3$  (see the Text and L04). Open histogram with dotted line (blue on the web): model expressed by equation (7) for  $\gamma = 50$ ,  $m = 2.4$  and  $\beta = -2$  [see the Text and Conselice (2006)]. Open histogram with dot-dashed line (green on the web): flat distribution. *Top panel:* total merger rate (hatched histogram, red on the web). Open histogram with dashed line: equation (5) for  $m = 3.3$ . Open histogram with dotted line (blue on the web): equation (7) for  $\gamma = 5000$ ,  $m = 2.4$  and  $\beta = -2$ .

However, the simulated CRG rate can be fit also by a flat distribution with  $N_{\text{CRG}} = 5.0$  (non-reduced  $\chi^2 = 12.4$  and null hypothesis probability equal to 0.19, for 10 data points, 1 parameter and Poissonian errors).

In Section 3.3 we stressed that the CRG formation rate is a good tracer of the merger rate. For comparison, the top panel of Figure 5 shows the evolution with redshift of the total merger rate (i.e. the merger rate of halos with mass between  $5 \times 10^{12}$  and  $10^{14} M_{\odot}$  at  $z = 0$ ).

In this Figure, the total merger rate is compared with the Carlberg model (dashed line) and with Conselice’s formula (dotted line). Even in this case, the Carlberg model ( $m = 3.3$ ) does not match results from simulations, as it predicts an increase of the number of mergers with redshift. Instead, Conselice’s formula is in better agreement with the simulated merger rate. In particular, the best-matching parameters for equation (7) are  $\gamma=5000$ ,  $m=2.4$  and  $\beta=-2.0$ . Then, Conselice’s formula reproduces the evolution of the CRG formation rate as well as of the total merger rate.

#### 4 SUMMARY

We have used cosmological numerical simulations to study the rate of mergers of halos with mass  $> 5 \times 10^{12} M_{\odot}$  and the CRG formation rate. The large volume combined with the selection criterion used to identify halo progenitors allows us to quantify the cosmic merger fraction, the merger rate

and the CRG formation rate among halos. We have made comparisons between these and theoretical models and the latest available observational data.

Our main conclusions may be summarized as follows.

- The merger fraction of progenitors of the present day galaxies does not evolve strongly with the redshift between  $0.2 \leq z \leq 2$ . Predictions of the merger fraction and merger rates are in fair agreement with the current observational data, within the great uncertainties. This implies that the observed decrease of the cosmic star formation rate since  $z \sim 1$  is not tied to a disappearing population of major mergers, at least according to our models. We calculate that the number of mergers a progenitor of a halo with mass  $> 5 \times 10^{12} M_{\odot}$  will undergo from  $z = 2$  to  $z = 0.2$  is  $N_m \sim 2$ . We find that there are still major mergers occurring at redshift lower than  $z \sim 1$ , mainly due to the late assembly of large mass systems.
- The formation rate of CRGs is a good tracer of the merger rate.
- Assuming that the galaxy interaction rate per unit volume is proportional to  $(1+z)^m$ , as suggested by previous models, we derive  $m = 3 - 4$  from our numerical simulations of the concordance cosmological model. However, the CRG formation rate as well as the global (major+minor) merger rate are best-matched by the formula  $N_{\text{merger}} = \gamma (1+z)^m \exp[\beta(1+z)]$  (Conselice 2006).
- The CRG formation rate inferred by simulations is in marginal agreement with the observed CRGs between  $0.2 \leq z \leq 1$ . However, new redshift measurements are required to have a good statistical sample of CRGs. Future surveys like zCOSMOS will be able to provide insights on the incidence of galaxy mergers and CRGs rates, and will be extremely useful to test the rates predicted in the hierarchical universe.

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